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REPORT



## Interdisciplinary studies of solar activity and climate change

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### 1. Introduction

The solar flux is considered the fundamental energy source of earth's climate system, and the earth's motion greatly influences climate change over long time scales (Imbrie and Imbrie 1980; Ruddiman 2001). Modern global climate change is one of the core issues in research on climate change. The degree to which astronomy and earth motion factors, which are characterized by quite weak and slow variations, contribute to climate change remains unclear (Beer 2006; de Jager 2008; Wang et al. 2010). Notably, in recent decades, some studies have noted that the nonlinear process in a climate system could amplify tiny variations in astronomy and earth motion factors (Lean and Rind 2001; Gray et al. 2010). For example, the principle 'bottom-up' mechanism of solar effects on the Pacific climate system could be assisted by nonlinear and positive air-sea feedback in the cloud-free area of the subtropical Pacific and tropical precipitation zone (Meehl et al. 2008, 2009). In the 'top-down' influence of solar UV irradiance that propagates from the stratosphere to the troposphere, the small initial variation of solar signal could be amplified via the wave-mean flow interaction (Kodera and Kuroda 2002; Matthes et al. 2006; Kodera et al. 2016). Therefore, we should not neglect the effects of these factors on global climate change. Indeed, astronomy and earth motion factors present intriguing and cutting-edge questions to better understand climate change.

However, the driving mechanisms behind astronomy and earth motion factors, as well as corresponding amplifying processes within the earth's climate system, are not fully understood. Moreover, qualitative evaluations of how these factors affect modern climate change, and particularly global warming over the last hundred years, have yet to reach a consensus. Due to the interdisciplinary nature of this subject, studies in this field were insufficient in China.

Thus, it is necessary to develop and enrich this research field in China. In 2012, China's National Basic Research Program examined the impacts of astronomy and earth motion factors on climate change. Led by Prof. XIAO Ziniu, the director of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics in the Institute of Atmospheric Physics (LASG/IAP), this program studied the relationships between astronomy and earth motion factors and earth's climate change, clarified relevant influencing mechanisms, and qualitatively assessed how these key factors contributed to past and future climate change. This five-year research program that involved scientists from atmospheric science, astronomy, earth science, marine science and space physics has greatly advanced our understanding of this interdisciplinary research field. Furthermore, the achievements accomplished through this program have begun to fill this knowledge gap in China. This interdisciplinary research team has laid a solid foundation for further study.

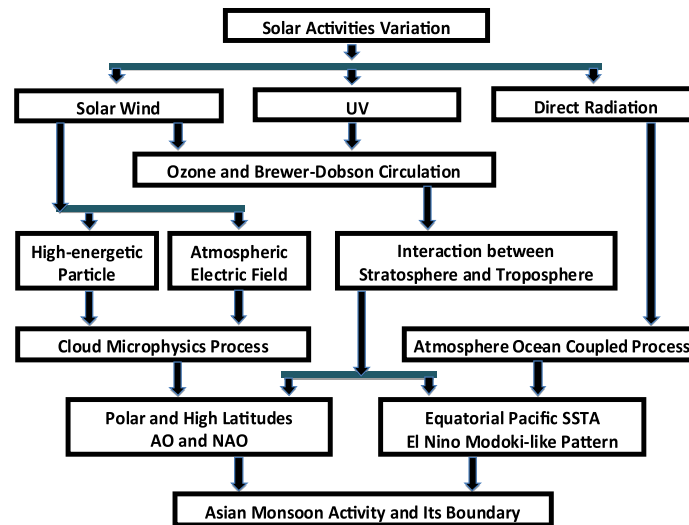
### 2. Major achievements

Our team conducted a series of studies that examined how astronomy and earth motion factors impacted climate change. To do so, we employed the combined technique of statistical analysis and numerical simulation. First, the key factors of astronomy and earth motion were identified. Then, new information on climate change obtained from the key factors was gleaned and the driving mechanisms behind these key factors on climate were verified. We then developed a theoretical framework and physical model based on this information. In addition, with the help of statistical and numerical models, the effects of these key factors on past climate change were validated successfully. We also projected how the key factors would impact future climate variation.

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**Figure 1.** The sketch of research on solar activity and climate change in this program.

This program concluded recently. As presented in Figure 1, the main studies on solar activity and climate change were carried out according to this sketch. The highlights achieved by our interdisciplinary research team include (1) proposing the key mechanism of solar wind and electric-microphysical effects on climate, and (2) constructing a physical model depicting the interdecadal response of the air-sea system to solar activity.

### **2.1. Solar wind and electric-microphysical process is the key mechanism that affects climate**

We investigated the influencing mechanism of high-energetic particle precipitation modulated by solar wind on the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). On a day-to-day time scale, Zhou, Tinsley, and Huang (2014) and Huang et al. (2013) found that the minima in AO and NAO indices only lagged 0–2 days of the solar wind speed (SWS) minima during years of high stratospheric aerosol loading, which suggests a much faster mechanism of solar influence on the atmospheric system compared to the ozone destruction process. From the perspective of year-to-year variation, Xiao and Li (2016) and Zhou et al. (2016) showed a robust relationship between SWS and NAO in boreal winter. These aforementioned studies indicate that the wintertime Iceland Low in the North Atlantic was very sensitive to solar wind variations and played an important role in the process of solar wind and electric-microphysical effects on climate. Moreover, under the condition of a weak electric field, we have demonstrated the marked impact of cloud droplet electricity on the collision efficiency of cloud condensation nuclei. This, in turn, suggests that the collision in a cloud microphysics process constitutes the core link between atmospheric electricity and climate (Tinsley and Leddon 2013; Tinsley and Zhou 2013, 2014). Furthermore, Tinsley and Zhou (2015)

improved the collision and parameterization scheme that varied with electric quantity in a cloud microphysics process and quantitatively evaluated the effects of high-energetic particle flux on cloud charge.

This achievement not only supports the marked association of solar activity with weather and climate change on various time scales, but also avails the quantitative accession of solar impacts on climate. It is worth noting that the successful establishment development of a theoretical model regarding of the influencing process of solar energetic particles on the atmosphere improves the development of global climate models.

### **2.2. Solar influence on and modulation of interdecadal variation in air-sea systems**

Due to the complexity in the response of air-sea system to solar variation, the full impacts of small changes in solar forcing on climate may be partly veiled. However, our research team found that, on an interdecadal time scale, the solar signal is more significant and detectable in some more sensitive regions, such as the tropical Pacific and monsoon regions. For example, a dipolar pattern of convection was firmly created in the tropical western Pacific and the maritime continent during the one to two years that followed peak years of solar cycle and was accompanied by an eastward shift of deep convection (Xiao, Liao, and Li 2016). Meanwhile, a lagged warming response was observed in the central Pacific both in sea surface temperature and in the main pycnocline of the ocean. Further work revealed that the lagged response of the tropical Pacific to solar cycle forcing can modulate the El Nino Modoki event on an interdecadal time scale through a combination of coupled atmosphere–ocean process and convection–cloud feedback (Huo and Xiao 2016, 2017). Interestingly, some fingerprints of the solar cycle in the East Asian

summer monsoon (EASM) were detected in our studies. It was first identified that the mean latitude of the rainband during the East Asian generalized Mei-Yu season was evidently modulated by the 11-yr sunspot cycle. This time period was just characterized by a large scale quasi-zonal monsoon rainband (Zhao and Wang 2014). This study also suggested that the north boundary of EASM may be more sensitive to solar forcing than its interior, resulting in a slight northward shift during high solar activity years (Wang and Zhao 2012; Zhao, Wang, and Zhao 2012). In addition, Wang et al. (2015), in examining the relationship between solar activity and wintertime in an East Asian climate, suggested an asymmetric solar influence on the winter climate in East Asia. Further research indicated that this relationship was robust during active solar periods, while the connection was fairly weak during inactive solar phases.

This observation study suggests a spatio-temporal selectivity in the responses of air-sea systems to solar variation, as well as an amplifying influence of the solar signal via synergistic interactions between the ocean and atmosphere in some sensitive regions.

### 3. Future studies

The five-year efforts of this program have promoted a greater understanding of how astronomy and earth motion factors influence climate change in China. More importantly, an interdisciplinary research team has established a solid foundation for further studies. The follow-up research is currently in progress and focuses on two main aspects: one is the effects of solar radiative forcing and solar energetic particles on climate in middle-high latitudes through modulating polar stratospheric-troposphere coupling, and the other is the response of a tropical Pacific air-sea system to interdecadal variation in solar activity and how this response propagates into middle latitudes through East Asian monsoon activity.

The latest study by Dr. ZHAO Liang and Prof. XIAO Ziniu from LASG/IAP reports a possible mechanism for amplifying the solar signal in the East Asian monsoon region. This study indicates that the dynamic responses of the lower tropical monsoon and the upper subtropical westerly jet to the 11-yr solar cycle, respectively, transmit bottom-up and top-down solar signals, which could amplify the solar signal in the north boundary of EASM (Zhao et al. 2017). Moreover, our team in LASG/IAP and East China Normal University recently perfected the numerical model simulations of collisions in a cloud microphysics process under the modulation of solar energetic particles. In taking advantage of these improved coupled models, we now aim to study in more detail how solar activity impacts weather and climate change.

### Disclosure statement

No potential conflict of interest was reported by the authors.

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